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INVESTIGATION OF BOND QUALITY EFFECTS ON PIEZOELECTRIC SENSING OF IMPACT DAMAGE (PREPRINT)

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14. ABSTRACT
Elastic waves generated by foreign materials impacting surfaces of aerospace vehicle can be used to detect and quantify the severity of damage. Passive acoustical emission sensors, made of piezoelectric elements, are typically used as impact signal detection devices. In this study, we have concentrated on characterizing the bonding qualities of piezoelectric sensors in terms of various bonding materials and adhesion conditions such as bond strength, bond stiffness, partial bonding, and disbonding. The experiment has been performed with an automated impact testing setup under controlled bonding and disbonding conditions in an attempt to establish a standardized sensor bond quality inspection methodology.

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Investigation of Bond Quality Effects on Piezoelectric Sensing of Impact Damage

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ABSTRACT

Elastic waves generated by foreign materials impacting surfaces of aerospace vehicle can be used to detect and quantify the severity of damage. Passive acoustical emission sensors, made of piezoelectric elements, are typically used as impact signal detection devices. In this study, we have concentrated on characterizing the bonding qualities of piezoelectric sensors in terms of various bonding materials and adhesion conditions such as bond strength, bond stiffness, partial bonding, and disbonding. The experiment has been performed with an automated impact testing setup under controlled bonding and disbonding conditions in an attempt to establish a standardized sensor bond quality inspection methodology.

Keywords: PVDF, SHM, stretch direction, elastic waves, acoustic emission, bond quality, impact damage detection

1. INTRODUCTION

Piezoelectric sensors are often preferred over other types of sensing systems (e.g. fiber optic, strain gauges, etc.) for damage characterization and assessment in many structural health monitoring (SHM) applications. Among the most widely used piezoelectric sensors, PZT (Lead Zirconium Titanate) ceramic materials offer an inexpensive choice, and are available in wide variety of shapes, thicknesses, and vibration modes. Since PZT ceramics are inherently brittle and non-flexible, however, in some applications they are not the optimized sensor choice. The use of rigid sensors on curved or porous surfaces, for instance, represents a significant technical challenge. Several recent studies have proven that polymeric piezoelectric sensors work better than rigid sensors on various structural materials[1-5].

Polyvinylidene Flouride (PVDF) thin films are one of the most widely used polymeric piezoelectric materials used for sensing acoustic signals from milli-hertz to mega-hertz frequencies. PVDF film consists of long polymer chains of repeating monomer, $-CH_2-CF_2-$. The electric charges of the hydrogen and fluoride atoms are positive and negative with respect to the carbon atoms, respectively, where the inherent electric dipole moment comes from this charging configuration of each monomer unit. During the process of manufacturing, the PVDF film in molten phase is solidified and stretched in a particular direction before polling. After stretching, the polymer chains are mostly aligned along the direction of stretch. This stretching process and polling imparts a permanent dipole moment to the film, which permits the PVDF to behave like a piezoelectric material.

Since the stretching introduces a preferred alignment direction for the dipole moment, PVDF film is anisotropic in terms of piezoelectricity. The values of piezo strain constants d_{31}, d_{32} and d_{33} for PVDF are given in Figure 1 along with the definition of axes for the each constant. As one can notice, d_{31} is much higher than d_{32}. The effect of the PVDF stretch direction to the detection sensitivity of low energy impact signals was investigated in this work.

In addition to the effect of sensor stretch direction, we have also concentrated on understanding the signal responses of various sizes of sensors made of PVDF film for low energy impact signals generated by tapping the surface of test block with a ball bearing attached to an electric solenoid. Various sensors with different surface areas and bonding materials were tested to characterize their signal responses. The performance of fully bonded and partially bonded PVDF sensors (Figure 2) has also been investigated.

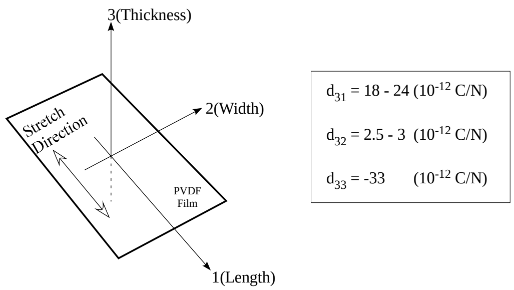

Fig. 1. Piezo strain constants of PVDF film and definition of axes.

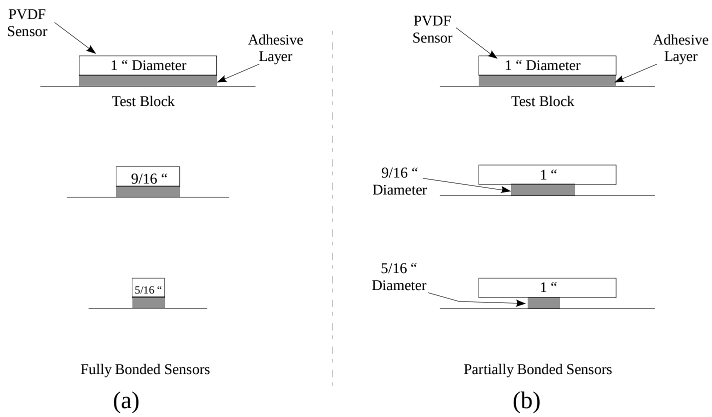

Fig. 2. Schematic drawing for fully bonded sensors (a) and partially bonded sensors (b) with various diameters.

2. EXPERIMENT

2.1 Setup and test block

An electric solenoid mounted vertically above an aluminum 7075 test block was controlled by a pulse generator and relay control circuit to retract momentarily and drop freely on the test block surface to generate stress waves. A block diagram for the setup is shown in Figure 3a. By varying the DC voltage to the solenoid and its pulse width, the drop height could be controlled and adjusted. A steel ball bearing with diameter of 0.187" was attached at the lower end of the solenoid rod. For the present work, the height was fixed to 5/16 of an inch at which no visible surface damage to the block was observed. A low pass filter, amplifier and digital oscilloscope were used to collect the signal from the PVDF sensor, and to trigger the drop of the solenoid actuator through a pulse generator and the relay control circuit.

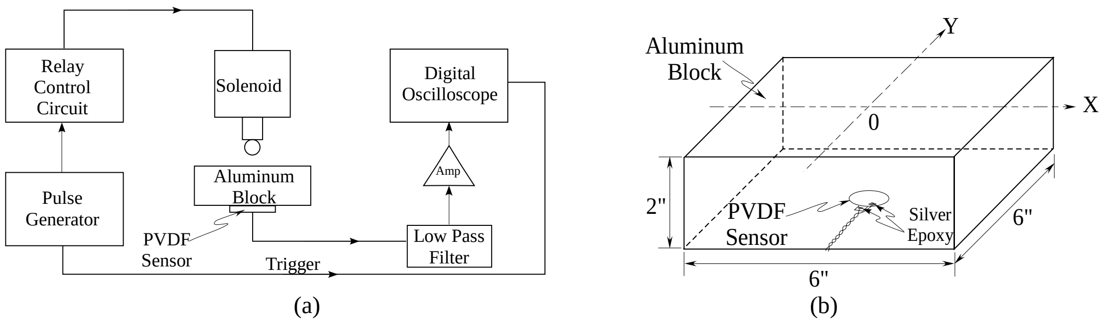

Fig. 3. Block diagram for the controlled tap test experiment (a) and schematic drawing of test block with sensor location (b).

A schematic drawing of the test block shown in Figure 3b depicts the PVDF sensor bonded on the bottom surface of the block with various adhesives. Three different sizes of sensors were tested with four different types of adhesives. Table 1 shows the sensor size and adhesive materials used for the present work.

Table 1. Various sizes of sensors and bond materials used in the study.

Diameter	Bond Material
1 inch (=2.5 cm)	5 Minute Epoxy
9/16 inch (=1.4 cm)	M-Bond 200
5/16 inch (=0.8 cm)	Spray-on Adhesive
	Double Sided Scotch Tape

2.2 PVDF sensors and mapping coordinates

A schematic drawing of a circular PVDF sensor is shown in Figure 4. The thickness of PVDF film used to make sensors was 120 μm. Sensors were bonded on the bottom surface of test block (Figure 3b) so that the stretch direction was parallel to Y-axis of mapping direction. Signal wires were attached on the surface of the sensor with a conductive adhesive as shown in the Figure 4. In order to ensure the electrical conductivity and mechanical strength of adhered areas, the epoxied wires were left to cure/harden overnight. The graph in Figure 5 shows the electrical resistance of conductive epoxy as a function of distance after an overnight cure. The nominal thickness of the conductive layer tested was approximately 0.01 inches.

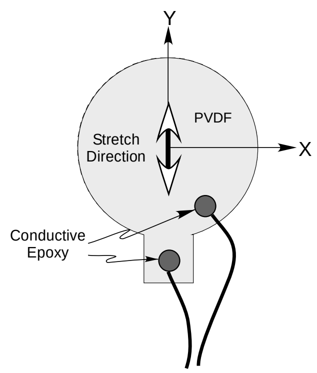

Fig. 4. Schematic drawing of PVDF sensor with stretch direction and signal wires attached to the surface.

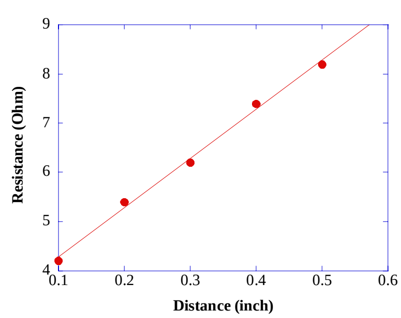

Fig. 5. Electrical resistance of conductive epoxy as a function of distance (0.01” thick layer was used).

Figure 6 shows the tick marks drawn on the top surface of test block with X and Y coordinates used for data collection. The smallest tick marks correspond to ¼ of an inch. Impact measurements were taken at various X and Y coordinate positions on the top of the aluminum block surface, with the bonded PVDF sensor being kept stationary relative to the X=0 and Y=0 position on the bottom of the block.

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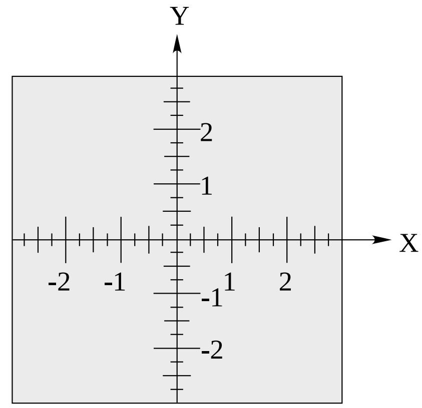
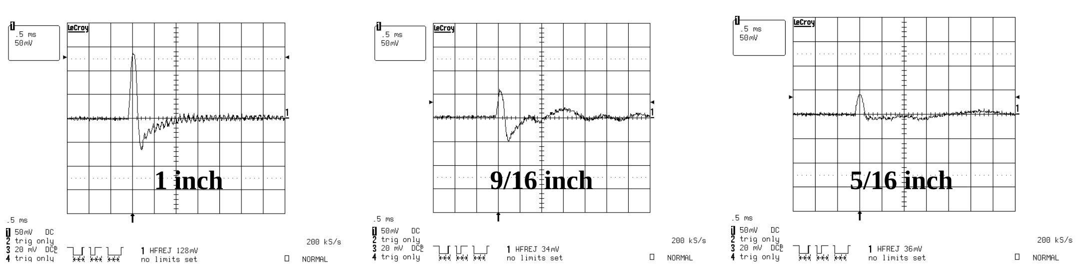


Fig. 6. Tick marks on the surface of test block with X and Y mapping coordinates.

3. EXPERIMENTAL RESULTS AND DISCUSSIONS

3.1 Low energy impact signals

Examples of low energy impact signals detected by different size PVDF sensors are shown in Figure 7. For the present experiment, the first peak signal following the zero voltage crossing line was measured instead of peak to peak voltage. It was found during the course of experiments that the peak to peak signal varied widely depending on the size of sensors, the location of impact, and the X-Y direction along which the impact test was performed. A peak to peak voltage measurement was thought be more complicated than a simple impulse signal measurement for the present investigation. The uncertainty of peak voltage measurement for the present work was estimated to be less than ±3%.



(a) (b) (c)

Fig. 7. Waveforms of received signals with various sizes of PVDF sensors; 1 inch (a), 9/16 inch (b) and 5/16 inch (c) diameters. Double sided scotch tape was used as bond material and center of the block was impacted.

As one would expect intuitively, the response of the piezo sensors decrease as the impact spot is moved away from the sensor. For a smaller sensor size, the overall signal response was found to be weaker than for bigger sensor as depicted in Figure 7. The linear graph in Figure 8 shows the relationship between the peak signal and surface area of PVDF detecting sensors. As the surface area of PVDF sensor gets larger, the signal response increases linearly.

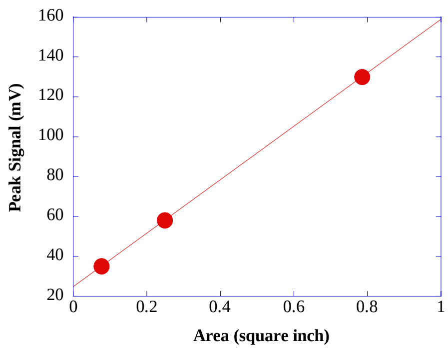


Fig. 8. Linear relationship between peak signal and surface area of PVDF sensors.

3.1 Fully bonded sensors with various adhesives

Signal responses of fully bonded PVDF sensors with various diameters and bond materials are shown in Figure 9. In each set of graph, both X- and Y-axis signal responses are plotted as a function of distance from the center. For a better comparison, the signal level is normalized to the peak signal of center impact.

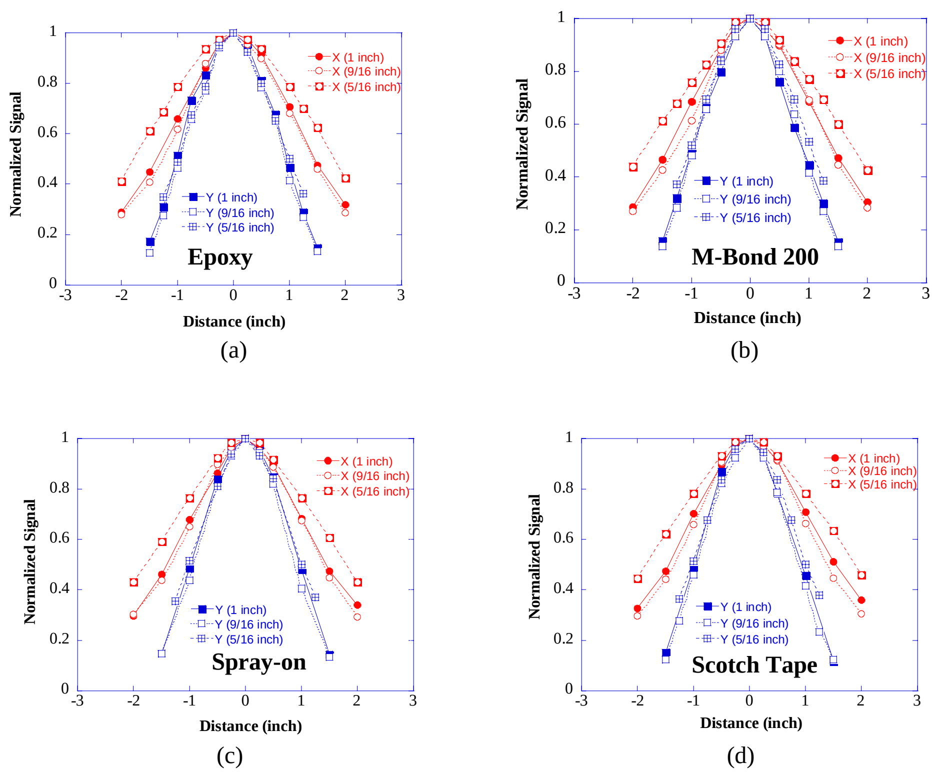


Fig. 9. Normalized signal responses of PVDF films with different diameter sensors and bond materials; epoxy (a), M-Bond 200 (b), spray-on (c) and double sided scotch tape (d).

The graph in Figure 9a depicts the results for epoxy as bond material, where the three inner curves correspond to the Y-axis (stretch direction) response and the outer three curves correspond to the X-axis response. Additional bond material results are depicted in Figures. 8b, 8c, and 8d, where it is clear that the signals detected along the Y-axis consistently overlap on top of each other even though the sizes of sensors are different. For signals along X-axis, however, are noticed to be different from the Y-axis. The three X-axis responses are wider in width meaning that the signal dissipation ratio is lower than for the Y-axis. There is, therefore, a preferred direction in the response to the impact signals. This directionality was found throughout the entire experimental results.

In the case of the 5/16" (= 0.8cm) diameter sensor, the response curves along the X-axis is even wider in width compared to other two larger sensors (1 inch and 9/16 inch). This applies to all four different adhesive materials. Although the overall signals detected with the 5/16 inch sensor were found to be weaker than the other two larger sensors, the dissipation ratio, which is more sensitive to the impact spot as it moves away from the impact/sensor center, is lower than the bigger diameter sensor case.

The graphs in Figure 10 show the effect of different bond materials on the response of the PVDF sensors with various diameters. There is no noticeable difference between the four different types of bond materials used for the present investigation. In each graph, however, one can notice that the width of signal response curves along Y-axis, stretch direction, is much narrower than X-axis. Once again the signal dissipation ratio for the 5/16 inch sensor (Figure 10c), along X-axis is lower than the other two sizes. There are no differences along Y-axis for different size sensors.

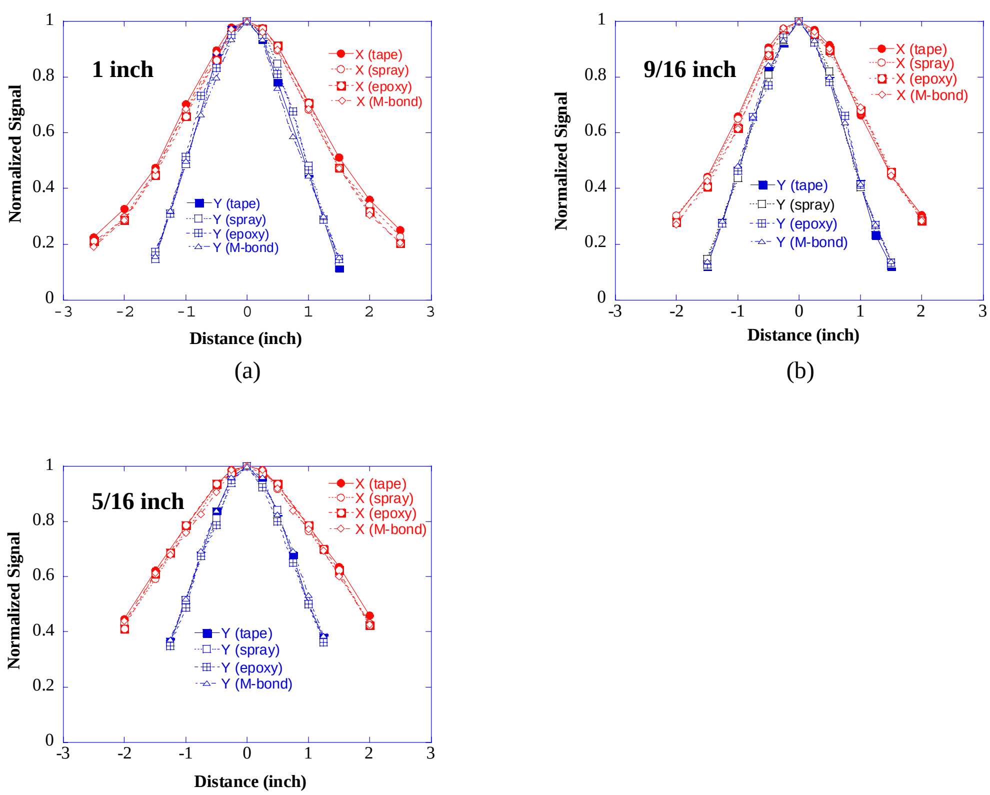


Fig. 10. Effect of bond materials for PVDF sensors with different sensor diameters. Normalized signal responses of PVDF films with different bond materials and 1 inch (a), 9/16 inch (b) and 5/16 inch (c) diameter sensors.

3.2 Partially bonded sensors

Often times, sensors fully bonded to a surface can be degraded as time passes due to mechanical vibrations, humidity, or aging of bond materials. Therefore, it is important to understand how partially bonded sensors respond to impact signals when they are used for integrated structure health monitoring (ISHM) applications.

The graphs in Figure 11 show the experimental results. The three inner curves correspond to the signal responses along the Y-axis, stretch direction of the film, while the outer three curves are along X-axis. As the bonded area gets smaller, the responses along the Y-axis become more asymmetric and narrower in width. On the other hand, the responses along the X-axis maintain the symmetry and become wider as bonded area gets smaller. This means that the overall signal response decreases as the active surface area becomes smaller, but the signal dissipation ratio becomes lower compared to the bigger bonded area results. These results are consistent with the experimental results described in the previous sections.

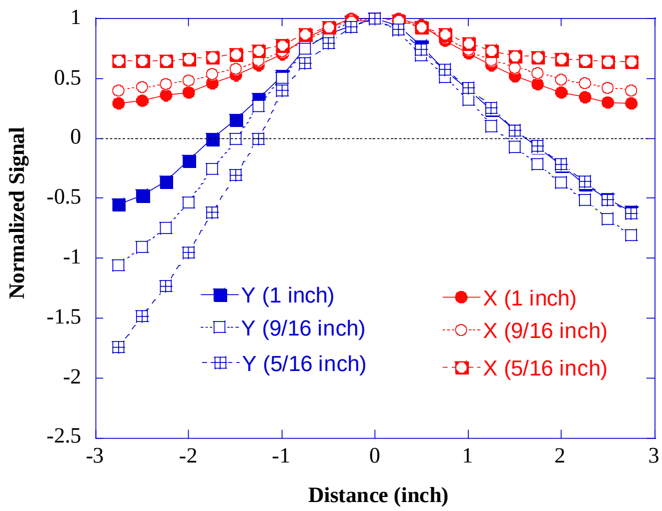
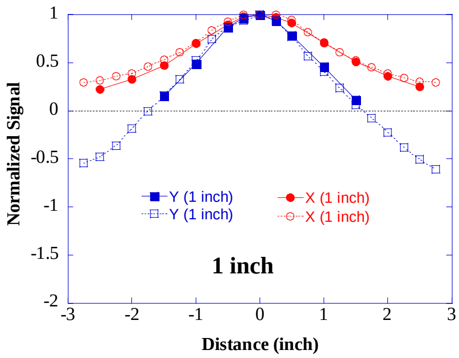


Fig. 11. Signal responses of PVDF sensors with various bonded areas.

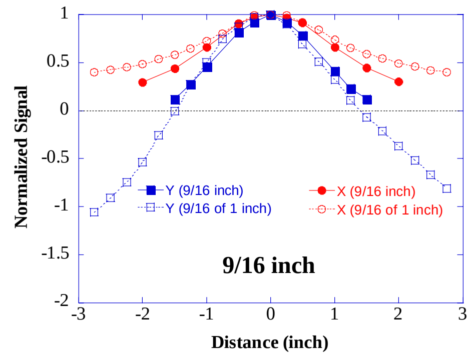
3.3 Comparison of fully and partially bonded sensors

Two groups of sensors with different sizes and different bonded areas were compared for their responses to impact signals. Experimental results of various sizes of sensors described in sections 3-2 and 3-3 are compared and are plotted together in Figure 12a. Signal responses of both fully and partially bonded sensors along the Y-axis overlap on top of each other, except for the asymmetric feature of the partially bonded sensors with diameters of 9/16 and 5/16 inches, Figures 12b and 12c, respectively.

Along the X-axis, both the 9/16 and 5/16 inch partially bonded signals show lower signal dissipation ratios as the impact spot moves further away from the sensor location compared to signal responses of fully bonded cases. It should be noted that the signal dissipation ratio for all three fully bonded sensors is approximately the same regardless of the size. In other words, the signal dissipation ratio of partially bonded sensor is lower than a fully bonded sensor if the diameter of bonded area is the same.



(a)



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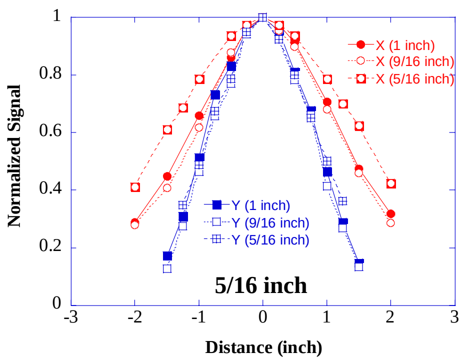

(c)

Fig. 12. Comparison of signal responses of PVDF sensors with various bonded areas and sizes; 1 inch (a), 9/16 inch (b) and 5/16 inch (c) of diameters.

4. CONCLUSIONS AND FUTURE WORK

The stretch direction of PVDF film affects the response of the sensors to impact signals. Along the stretch direction, impact signals dissipate at a higher rate than for the perpendicular direction as the impact area moves further away from the sensor location. This effect is observed for sensors with different diameters and bond conditions. For fully bonded sensors, the effect is fairly consistent regardless of surface area of sensors and symmetric response curves. In the case of partially bonded, however, signal response curves gets more asymmetric as the surface area of the sensor gets smaller.

The effect of bond materials is not pronounced among the four different bond materials (epoxy, M-Bond 200, spray-on, and double sided scotch tape) that were tested in the present work. Impact signal responses along both the X- and Y-axis are very similar. The results of fully bonded sensors with different diameters showed that the smallest sensor (5/16 inch in diameter) has a slightly lower dissipation ratio along the X-axis, but the larger sensors (9/16 and 1 inch) have the same impact signal responses. In the case of partially bonded sensors, however, the overall peak signal goes down as the bonded area sets smaller. Smaller bonded sensors show lower dissipation ratios as the impact area moves away from the sensor location.

For the present investigation, we have collected impact data along the X- and Y-axes, and it is clear that the stretch direction of PVDF film affects sensor response. It is important to collect more impact data over the entire area of test block to understand the anisotropic characteristics associated with the stretch direction. Since each data collection

process is tedious and time consuming, an automated two dimensional mapping system is being designed. More testing is also expected with piezoelectric materials, PZT ceramics and $LiNbO_3$ single crystals, on various aerospace structure materials such as carbon fiber composites, honeycombs and multilayered structures.

Embedded ISHM sensors made of various sensing materials can also be tested with an automated tapping test for their acoustic emission signal responses. Simple tapping tests for embedded sensors can verify the integrity of sensors in the material once the low energy signal responses of those sensors are understood under a controlled environment. As the current investigation shows, bond condition of sensors can influence the ability of sensors to detect impact events.

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